Small–scale rifting during paroxysmal eruptive episodes at the South East Crater of Mount Etna (Sicily)

Marco Fulle* & Boris Behncke†

* Osservatorio Astronomico, Via Tiepolo 11, I–34131 Trieste, Italy

† Dipartimento di Scienze Geologiche, Palazzo delle Scienze, Corso Italia 55, I–95129 Catania, Italy

Mount Etna (Sicily) began a new period of exceptional eruptive activity on 26 January 2000. This activity consists of brief but violent episodes of fire fountaining from the South East Crater (SEC hereafter), preceded by hours of quiet effusive activity, which indicates that the magma conduit is open and close to equilibrium between two paroxysms. This makes it difficult to understand what triggers the abrupt onset of the fire fountain episodes, which sometimes start within a few seconds. Here we show that a possible explanation is given by the sudden lateral enlargement of a fracture lying below the SEC: structural instabilities linked to the rising magma or tectonic movements lead to the enlargement of the magma dyke by up to 0.8 m in each episode, sufficient to cause the sudden transition from quiet effusive activity to violent degassing and fire fountaining. If field measurements will confirm dilatation of the eruptive fracture during each SEC paroxysm, and if this activity, which so far has consisted of 66 episodes, will continue, this process might lead to the gravitational collapse of a section of the western rim of the Valle del Bove and of the SEC cone itself.

Following a major eruption on the upper SE flank in 1991–1993[1], eruptive activity resumed at the summit craters of Mount Etna in mid 1995 and has continued with few interruptions through late August 2000. While all four summit craters were sometimes erupting until November 1999, most activity is concentrated at the SEC since the beginning of 2000. Each eruptive episode involves a NNE–SSW trending fissure cutting through the SEC (Fig. 1). This fact merits special attention since the SEC sits on a system of volcano–tectonic fractures[2] which extends in two arms to the ENE and to the SE. Since the late 1970s, eruptions on this fracture system were often preceded or accompanied by strong activity at the SEC, and the fracturing of its cone in each eruptive episode during the year 2000 shows that at least the central portion of the system is still unstable.

Observations[3,4] from close range (from 1 to 3 km, Fig. 2) of many SEC paroxysms have shown that all of them follow a general evolutional scheme. After hours or days of silence, slow effusive activity begins at one of the lower ends of the fissure. During hours of effusive activity, the outflow rate increases, along with voluminous gas emission from the SEC top vent, and then spattering begins at the effusive vent. Then, weak strombolian activity starts along the whole length of the fissure, which may last for a few minutes to a few hours. The fire fountains start abruptly and soon rise to mean heights of 500 m, with bursts rising higher than 1 km, while a tephra–laden eruption column rises 4–8 km above the summit. The fountains involve the whole fissure, although the highest ones are ejected from the SEC top vent. Minor lava flows are ejected along all the eruptive fissure, probably due to the fall of the fountain into the fissure itself, so that this lava is pushed laterally into these minor flows by the rising fresh lava. The end of the fountain is even more abrupt than its beginning.

The sudden onset of violent magmatic degassing is certainly caused by instantaneous decompression of the magma rising in the conduit, which could be explained by the uprise of a fresh batch of gas–rich magma. This would push residual and degassed magma from the previous episode out of the conduit. Once this residual lava is exhausted, the fresh magma would start degassing explosively, leading to the onset of fire fountains. However, the long time spent by the residual degassed magma in the conduit between two paroxysms makes this hypothesis improbable: in most cases the quiet interval lasted several days, with the extreme case of the 65th eruptive episode, which occurred after more than 2 months of quiet. In this event, slow lava effusion went on for about 30 hours before strombolian activity began at the summit vent, followed by the usual abrupt onset of the paroxysmal phase. It is unlikely that the magma which was extruded during the first 30 hours of activity was left over after the previous eruptive episode and had resided in the conduit for 2 months without cooling significantly.

Here we consider an alternative interpretation by means of a model which allows us to investigate how the fountain's onset depends on the physical parameters of a mixture of liquid magma and gas bubbles (assumed to be composed mainly of water vapour). Eqs.(A1)–(A10) show that, when the bubbles reach a significant volume, the mixture mean density ρ is given by

$$\frac{1}{\rho} = \frac{1}{\rho_m} + \sqrt{\frac{L\ w^3\ g}{12\ \mu\ Q}}\ \exp\left[-0.68\ g\ \frac{z + z_0}{v_s^2}\right] \tag{1}$$

where $\rho_m = 2.6\ 10^3$ kg m^{-3} is the melt basalt bulk density[5], L and w are the length and the mean width of the magma dyke ($w << L$), $g = 9.8$ m s^{-2} is the gravitational acceleration, μ is the viscosity of the magma–gas mixture, Q is the mass supply rate of magma from the magma chamber[6] or directly from the mantle[7], z is the depth ($z = 0$ at the vent), z_0 depends on the magma fragmentation depth, and v_s is the sound speed in the fountain. The observed[3,4] height $h \approx 500$ m of the lava fountains provides the balistic speed at the vent $v_b = \sqrt{2gh} \approx 100$ m s^{-1}. Observations[3,4] suggest that the flow in the SEC fountains is dispersed rather than annular[8], so that the lava speed at the vent provides the sound speed[9] v_s [Eq.(A6)].

During the magma ascent the bubbles grow, so that ρ decreases. When ρ reaches a critical value ρ_c at a critical depth z_c, the bubbles are big enough to give rise to spattering (magma fragmentation) at the top of the magma dyke: here the magma degasses, and the released gas exits through the SEC vent. The remaining degassed lava reaches the surface as a slow lava flow, pushed laterally by the magma rising below, through an effusive vent lying z_c meters lower than the SEC top. Magma fragmentation occurs when the bubbles occupy 80% of the magma volume[8,9,10], i.e. $\rho_c = 0.2\ \rho_m$. Observations[3,4] suggest $z_c \approx 200$ m. Estimates[3,4] of the lava and tephra outflow during the SEC fountains suggest that Q does not exceed 5 10^5 kg s^{-1}. The length of the observed eruptive fissure on the SEC suggests[3,4] $L \approx 300$ m. In this case, we can have a fire fountain episode if the mean fissure width is

$$w \approx \frac{3\ Q}{2\ L\ \rho_c\ v_s} \tag{2}$$

which provides $w \approx 5$ cm for the assumed ρ_c. If $w >> 5$ cm, the fluid speed cannot approach v_s at z deeper than z_c, so that a fire fountain cannot start before strombolian spattering degasses the magma and inhibits its formation. The SEC eruptive fissure is much wider than 5 cm, because it ejects also meter sized bombs[3,4]. In other words, the SEC fissure is so wide (or Q is so low) that the magma cannot approach v_s at the top of the magma dyke (where it rises with speeds close to 1 m s^{-1}).

During all the effusive phase preceding the fire fountains, the magma dyke is at equilibrium, so that the lava output rate provides Q, which increases in time from the onset of the lava flow ($Q < 10^3$ kg s^{-1}) to shortly before the paroxysm ($Q \approx 5\ 10^5$ kg s^{-1}). However, continuous changes of Q in Eq.(1) are only responsible for a continuous change of the z_0 value (if z_c is observed to remain the same): we cannot obtain the onset of a fire fountain with continuous changes of the parameters. A fire fountain can be triggered only by a sudden jump of ρ below ρ_c: then the magma with gas bubbles transforms itself into a gas with lava clasts. According to the rockburst model[10], the fluid viscosity drops by many orders of magnitude and the pressure jumps from

$$P_c = \frac{\rho_m\ \rho_c\ v_s^2}{\rho_m -\ \rho_c} \tag{3}$$

at the top of the magma dyke ($P_c \approx 6.5$ MPa) to $P_a = 65$ kPa in the atmosphere at 3300 m a.s.l., so that the density decreases of a factor $P_c/P_a \approx 100$ (here we assume that in the fountain the lava clasts maintain the gas temperature at the magma one). Since the same Q must cross the remaining fissure up to the vent, the fluid must suddenly reach the sound speed: we obtain the onset of a fire fountain. The fissure mean width is then

$$w = \frac{Q\ P_c}{L\ v_s\ \rho_c\ P_a} \tag{4}$$

which provides $w = 3$ m, a value close to other width estimates of active dykes on Mount Etna[1]. This process converts a slice Δz deep of the magma dyke into the fountain lasting a time[3,4] $\Delta t \approx 600$ s

$$\Delta z = \frac{Q\ \Delta t}{w\ L\ \rho_c} = \frac{P_a}{P_c}\ v_s\ \Delta t \tag{5}$$

providing $\Delta z \approx 600$ m. Some fire fountain episodes have lasted up to half an hour[3,4]. However, in these cases the fountains were lower, probably due to a lower water content in the magma [Eq.(A6)]. The lower sound speed balances the longer fountain duration, so that Δz remains roughly the same. The dyke volume converted into a fountain is therefore $V = L\ w\ \Delta z \approx 6\ 10^5\ \mathrm{m}^3$ per SEC paroxysm.

Let us consider a sudden increase of Q in Eq.(1). This has the effect of increasing the mixture density, i.e. of decreasing the bubble size and probably also the mixture viscosity[5] of an amount balancing the increase of Q. So, a sudden increase of Q is useless for our purposes. On the contary, if w increases suddenly, we obtain exactly what we want: a jump of ρ below ρ_c. Note that only a sudden increase of w can lead to this due to the structure of Eq.(1), which is highly sensitive to small changes of w. Therefore, we propose that the dyke enlargement is the trigger of the sudden onset of fire fountains at the SEC. Eq.(A11) shows that the volume V is converted into the required fountain if w increases by 27%, i.e. about 0.8 m per paroxysm.

The increase of the dyke width may well be linked to the pressure of the magma rising in the dyke itself, which is close to P_c along all the slice Δz deep. The pressure of the surrounding rocks is higher[9] than P_c: this instability, coupled to the low viscosity of melt basalt, might cause some movements along the fracture providing the enlargement of the magma dyke. We point out that this model requires a fracture enlargement of about 0.8 m at a depth $\Delta z + z_c \approx 800$ m only: at the vent, it may be much lower (i.e., we provide an upper limit of the observable enlargement). The increase of the dyke width may be instantaneous or, more probably, distributed in discrete steps during the fountain episode. Field deformation measurements are needed to support this model and to provide information on its details. If they were indeed to confirm that these enlargements cumulate at every paroxysm, the SEC activity would largely increase the gravitational instability already observed below the SEC[1,2]. The effects of a sector of the western rim of Valle del Bove descending as a landslide down the eastern flank of Mount Etna towards the Ionian Sea could be catastrophic, and this possibility, in our view, requires immediate investigation.

Method

The equations describing a magma–gas mixture[9] are the pressure gradient equation of a viscous fluid in a dyke, the gas concentration equation, and the gas state equation

$$\frac{dP}{dz} = \frac{12\ \mu\ Q}{\rho\ L\ w^3} + \rho\ g \tag{A1}$$

$$\frac{1}{\rho} = \frac{f}{\rho_g} + \frac{1-f}{\rho_m} \tag{A2}$$

$$P = \rho_g\ K\ T \tag{A3}$$

where P is the pressure of the gas–magma mixture, ρ_g is the gas density, f is the mass fraction of water in the magma, $K = 460$ m^2 s^{-2} K^{-1} is the gas constant of water vapour, and $T = 1400$ K is the magma–gas temperature. Later we show that for melt basalt possible μ changes can be neglected.

We introduce the non–dimensional depth x and pressure y

$$x = \frac{g\ z}{f\ K\ T} \tag{A4}$$

$$y = \frac{P}{f\ \rho_m\ K\ T} \tag{A5}$$

The sound speed is

$$v_s = \sqrt{\frac{dP}{d\rho}} = (1+y)\sqrt{f\ K\ T} \tag{A6}$$

which in the fountain becomes $v_s = \sqrt{f\ K\ T}$, so that $v_s = v_b$ provides $f \approx 1.5\%$. We point out that this value is a rough approximation only, since the motion in the fountain is highly turbulent. However, Eqs.(A1)–(A5) are not very sensitive on the actual value of f: its changes imply a simple rescaling of the depth z and of the pressure P. Therefore, it is useless to consider f as a free model parameter. The computed f value is the water concentration at the top of the magma dyke. If gas flows through the dyke walls, f changes in time and is different from the original water content.

Eqs.(A1) – (A5) provide the following non–dimensional differential equation, when we approximate $1 - f \approx 1$

$$\frac{dy}{dx} = k\frac{1+y}{y} + \frac{y}{1+y} \tag{A7}$$

where k is the non–dimensional parameter

$$k = \frac{12\ \mu\ Q}{L\ w^3\ \rho_m^2\ g} \tag{A8}$$

For $k << 1$ the solution of Eq.(A7) is

$$y + \log_e \sqrt{1 + \frac{y^2}{k}} = x + x_0 \tag{A9}$$

where x_0 is the integration constant which must provide $y = y_c$ at $x = x_c$. A good approximation of Eq.(A9) is

$$y = \sqrt{k}\ \exp[0.68\ (x + x_0)] \tag{A10}$$

which provides errors lower than 1% of Eq.(A9) for $0.2 < y < 1$ and $k < 10^{-3}$. For $\mu = 100$ Pa s, $L = 300$ m, $w = 3$ m, $\rho_m = 2.6\ 10^3$ kg m^{-3} and $Q = 5\ 10^5$ kg s^{-1}, we obtain $k = 10^{-3}$, $y_c = 0.25$, $x_c = 0.2$, $x_0 = 2.8$. For melt basalt[5] $\mu < 100$ Pa s, so that for $Q < 5\ 10^5$ kg s^{-1} we get $k < 10^{-3}$. The low k value shows that the viscosity term gives a low contribution to Eq.(A7) when $y > y_c$. For $\mu = 10$ Pa s, the viscous term in Eq.(A7) is less than 0.25% of the weight one. Therefore, even if μ increases up to a factor 20 during the bubble growth[5], the error of the solution computed with μ constant remains lower than 5%.

From Eq.(A10) we obtain that small changes Δw compensate small changes Δx when

$$\frac{\Delta w}{w} = \frac{2}{3}\frac{\Delta y}{y} = 0.45\ \Delta x \tag{A11}$$

which is independent of any x_c at which the fountain starts.

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Figure Captions

Fig. 1 – Sketch map of the summit area of Mount Etna showing the four summit craters, the upper part of the Valle del Bove, and approximate extent of lava flows erupted from the SEC between January and June 2000. The eruptive fissure cutting through the SEC is indicated as a broken line.

Fig. 2 – Fire fountains about 700 m high during the 64th SEC paroxysm on Mount Etna, Sicily, on the evening of 24 June, 2000 (photo exposure 1 sec, ©Marco Fulle).